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INVESTIGATIONS OF DIELECTRIC-ROD FOCUSING FOR TRAVELING-WAVE TUBES

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Investigations of Dielectric-Rod Focusing for Traveling-Wave Tubes

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Relativistic electron-beam experiments by others have shown that thousands of amperes of field-emission beam current can be strongly contained and guided along the surface of a dielectric rod in vacuum. This report describes experiments to adapt this method to one-ampere, 8 to 15 kV electron beams to be used in military applications of traveling-wave tubes.

Results indicate that a plasma flare forms along the dielectric rod due to field emission induced breakdown. Electron emission occurs from the plasma at the end of the rod due to lateral

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20. Abstract (Continued)

conductivity of the plasma surrounding the dielectric rod. The dielectric rod acts as an extension of the cathode. This proposed explanation rules out the use of a dielectric rod as a focusing device within the microwave circuit, but the dielectric rod could possibly be useful for forming and guiding the beam to the entrance of the circuit. A titanium film electrode was used as a low-voltage trigger mechanism to initiate the plasma discharge. Such a trigger device can be used to eliminate a high-voltage high-power modulator and also to achieve consistent triggering from pulse to pulse.

CONTENTS

INVESTIGATIONS OF DIELECTRIC-ROD FOCUSING FOR TRAVELING-WAVE TUBES

I. INTRODUCTION

The objective of this research work was to devise and investigate new approaches towards achieving lighter weight and less expensive wide-bandwidth microwave power sources. The Navy has urgent needs for octave-bandwidth, inexpensive, lightweight microwave amplifiers in the 2-18 GHz range. Peak output power should be more than 100 watts. The only known device that will provide the bandwidth and power is the traveling-wave tube. Such tubes consist of a well-focused beam surrounded by a wire helix. Typical helix dimensions for this frequency range are about 1.5 mm inside diameter and 15 cm in length. The beam energy for optimum interaction must be approximately 8 to 15 kV. Present tubes utilize expensive magnets for beam focusing.

The major engineering and reliability problem is to maintain focus and alignment of the beam within the helix. The beam power, measured in kilowatts, is capable of melting the helix within microseconds if it were to strike the helix directly. The beam must be kept well within the helix diameter without striking the fragile helix except for a few stray electrons. A forceful mechanism to guide the beam within the helix or the forceful establishment of a fixed equilibrium diameter of the beam within the helix would be ideal solutions to the problem.

A number of focusing methods without the use of a magnetic field have been tried without great success. These are briefly reviewed in paragraph II-1. A new possible approach has appeared in the literature which is worthy of consideration.

In 1971 Bennett and his coworkers[1] described a simple cold electron emitter and electron beam guided on a dielectric rod without a magnetic field for focusing. The 3 MEV beam produces as much as 200,000 amperes of current. The dielectric rod provides such strong focusing forces that the rod can be bent into a 90° arc, and yet the beam follows the dielectric rod. If such a focusing system and cold cathode could be scaled to lower beam velocities, this would be a very worthwhile approach towards a substantial reduction in the cost of traveling-wave tubes. This report describes investigations and experiments to adapt the Bennett type focusing and cold emission to low-cost traveling-wave tubes.*

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*From the beginning, it has been clearly recognized by both management and research personnel that this project is a high risk but possibly a high payoff undertaking.

Note: Manuscript submitted June 8, 1976.

Bennett's experiments are with beam energies of 3 MEV, high currents, continuously pumped vacuum systems and pulse times of less than 100 nanoseconds. The present application at beam energies of 8 to 15 kV, beam currents of approximately one ampere and pulse time of 2 microseconds is an entirely different regime. However, Bennett's experiments show that the dielectric rod remains near cathode potential. Therefore, the electrons must be moving at a relatively low velocity near the dielectric rod. This implies that the strong focusing forces are present with low velocity beams. This fact encourages one to hope that the strong focusing forces may be present at lower tube potentials.

There are two distinct innovations involved. One is the dielectric-rod focusing and the other is the cold electron emission.

II. DIELECTRIC-ROD FOCUSING

1. Electrostatic Focusing Methods.

As background information it is useful to review briefly previously used electrostatic focusing methods (no magnets). Periodic electrostatic lens focusing with solid electron beams has been succesful[2-8] for narrow-band and low-power traveling-wave tubes. However, the focusing forces are not as strong as magnetic focusing, and the necessary microwave circuits to produce the electrostatic lenses are narrow bandwidth and costly.

Electrostatically focused hollow beams have been utilized in three ways. One approach[9] is "Harris Flow" in which a rotating annular beam is injected between two coaxial conducting cylindrical electrodes, the inner of which is maintained at a higher d-c potential. The radial electric field between the coaxial cylinders is adjusted to a value which will equal the centrifugal force acting on the electrons. Space charge repulsion forces within the beam add to the outward centrifugal force, but the space-charge forces are zero at the inner radius of the beam. Therefore, the rotational centrifugal force must be included so that a balance of forces can be achieved. A force balance at every radius of the beam would be possible only if the charge density of the injected beam could be made to vary as the inverse fourth power of the radius. This type of focusing has been used on low-power experimental tubes with the outer cylinder as the microwave circuit, but the tubes are narrow band mainly because the inner metallic rod within the circuit tends to eliminate the longitudinal microwave electric field.

A similar type of coaxial electrostatic focusing is utilized in the helitron oscillator[10] which also uses a rotating hollow beam to obtain an outward radial force balanced against the radial inward electrostatic force due to a positive potential on the inner cylinder. The difference is that the inner cylinder is the microwave circuit which produces both angular and radial components of microwave field. Electrons move towards the circuit when they lose energy to the circuit. This effect increases microwave interaction and efficiency and is similar to the "M" type interaction of magnetrons and other crossed-field tubes. The tubes are narrow band.

A third type of hollow-beam coaxial electrostatic focusing is accomplished by making the outer coaxial cylinder a series of ring-type lenses as shown in an excellent paper by C. C. Johnson.[11] These lenses, which are also the microwave circuit, cause inward converging forces on the beam. These inward forces are balanced against the outward electrostatic radial field due to a d-c negative potential on the inner cylinder. The lense-type microwave circuit is narrow band, but a perveance of 8×10^{-6} has been obtained with this type of focusing with good beam transmission. (Perveance is defined as $I/V^{3/2}$ where I is the beam current and V is the beam energy.)

To summarize, electrostatic focusing of a hollow beam has been successfully used between coaxial metallic cylinders with the microwave circuit either as part of the outer or inner cylinder. Focusing forces due to electrostatic lenses, centrifugal forces, and the radial electrostatic field between the cylinders have been employed. If the Bennett type of focusing is practical, then it would allow the outer cylinder to be a wide-band unifilar helix. The inner dielectric rod would have only minor effects on the longitudinal microwave fields. Thus, the Bennett-type focusing would be very compatible with wide bandwidth microwave circuits.

2. Space-Charge and Pinch Forces

It is assumed that the electron beam is moving parallel to and surrounding the dielectric rod as shown in Fig. 1. The focusing forces to maintain this condition will now be examined; while the initial establishment of the condition shown in Fig. 1 will be discussed in the following section on cold electron emission.

Bennett[1] et al ascribe the dominant focusing force to the self-focusing effect of the beam due to the beam's own magnetic field. The magnetic field of the beam produces an inward force and drives the beam towards the dielectric rod. This inward self-focusing of the beam is called the pinch effect. The opposing outward forces are space-charge repulsion and negative charge in or near the dielectric rod surface. It is well known that space charge outward forces are larger than the beam's inward pinch forces if there is no space-charge neutralization due to positive ions. However, Bennett et al assume a supply of positive ions which partially neutralize the space-charge force as due to:

(1) Ions formed by impact ionization with residual gas by the electron beam.
(2) Ions formed by particle collisions with the dielectric rod.
(3) Ions formed in the nearby volume moving towards the dielectric rod due to the negative charge on the rod and the beam.

It should be noted that whenever the beam density is high, as, for example, in the center of the beam, there is a potential depression within the beam due to the negative space charge. Any nearby positive ions will move towards this potential depression and can remain there for long periods of time. For example, positive ion neutralization of space charge by ion trapping in cylindrical beams has been possible even at pressures of 10^{-7} torr as shown by Ginzton and Wadia[12] and by Field.[13]

Since the objective application is to be a sealed-off tube which has a reasonable shelf life, high vacuum and well-outgassed electrodes are assumed. This means that neutralization of space charge by positive ions cannot be necessarily assumed. Since beams below 30 kV energy are being considered, relativistic corrections are not necessary. A uniform, constant-density laminar-flow beam, which is at a constant beam velocity and is located near the dielectric surface, is assumed as shown in Fig. 1. Positive ions, formed by impact collisions with neutrals, are assumed to be uniformly distributed with near zero initial velocity. (This assumption is somewhat questionable since positive ions tend to move to positions where the space charge potential depression is greatest.) The ratio of positive ions to electrons present per unit length of beam is f. The longitudinal beam velocity v is assumed to be undisturbed by collisions. MKS units are used throughout this report.

The outward space-charge force within the beam for the partially neutralized hollow beam can be obtained directly from Gauss' law:

$$F_S = eE = \frac{eJ\left(r^2 - r_1^2\right)}{2\epsilon_o v r}(1-f) \text{ for } r_1<r<r_2, \tag{1}$$

and outside the beam:

$$F_S = \frac{eJ\left(r_2^2 - r_1^2\right)}{2\epsilon_o v r}(1-f) \text{ for } r>r_2 \tag{2}$$

where F_S is the outward radial force of repulsion in newtons, J is the beam current density, e is the electron charge, r is the variable radius, r_1 is the inner beam radius, v is the beam velocity, and ϵ_o is 8.85×10^{-12} farads/meter. The radial distance from the inner radius to any radius within the beam is $(r-r_1)$. It should be pointed out that this nearly linear radially increasing force function depends upon the assumption that the beam is injected into the focusing system at a constant current density. If the injected current density varies with radius, then the force will vary as the current enclosed.

The inward "pinch" force within the electron beam, which opposes the outward space-charge force and which is caused by the self-magnetic field of the beam, can be obtained from Ampere's law:

$$F_m = ev\mu_o H_\phi = \frac{-ev\mu_o J}{2r}\left(r^2 - r_1^2\right) \text{ for } r_1<r<r_2, \tag{3}$$

and outside the beam:

$$F_m = -\frac{ev\mu_o J}{2r}\left(r_2^2 - r_1^2\right) \text{ for } r>r_2 \tag{4}$$

where F_m is the inward pinch force in newtons, μ_o is 1.26×10^{-6} henries/meter, and e, v, d, r_1, and r_2 are in MKS units. H is the magnetic field intensity.

If the surface of the dielectric rod is at a positive potential V_1 with respect to the outer cylinder (which may be the helix), then the resulting electrostatic field produces an inward force on electrons located between the cylinders. This inward force from Gauss' law is:

$$F_e = -\frac{(V_1 - V_3)}{\ell n \frac{r_3}{r_1}} \frac{e}{r} \text{ for } r_1<r<r_3 \tag{5}$$

where V_3 is the potential on the outer cylinder, V_1 is the surface potential of the dielectric rod, r_3 is the inside radius of the outer cylinder, r_2 is the radius of the dielectric rod, and r is the radius of the point at which the force is being calculated.

The force calculated from Eq. (5) depends on a positive potential at the surface of the dielectric rod. This positive potential can be due to the positive charging of the dielectric rod by electrons striking the rod causing secondary electrons to escape. More secondary electrons can escape than primary electrons arriving causing the rod to lose electrons and charge positively. The dielectric rod can also charge positively by positive ions striking the surface and recombining with surface electrons. On the other hand, the dielectric rod can charge negatively when the surface electric field conditions are unfavorable for collection of the emitted secondaries or that the number of emitted secondaries are fewer than the primary electrons.

The total of the outward radial forces acting on the electrons within the beam is the sum of Eqs. (1), (3) and (5):

$$F_t = \frac{eJ}{2\varepsilon_o v}\left(\frac{r^2 - r_1^2}{r}\right)\left(1 - f - \frac{v^2}{c^2}\right) - \frac{(V_1 - V_3)}{\ell n \frac{r_3}{r_1}} \frac{e}{r} \text{ for } r_1<r<r_2 \tag{6}$$

A similar equation, the sum of Eqs. (2), (4), and (5), could be written for the forces outside the beam. The first term in Eq. (6) contains a

$\frac{r^2 - r_1^2}{r}$ function which can be shown to be very nearly a linear increase in force as the radius within the beam increases. On the other hand, the force due to the second term (with the dielectric positively charged) decreases inversely as the radius. Therefore, the forces due to the first and second terms can be matched at only one radius. There could be a perfect balance of forces at all radii if the $(1-f-v^2/c^2)$ term were zero and if (V_1-V_3) were zero. If f were unity and V_1-V_3 were zero, then the v^2/c^2 inward pinch term would dominate. However, this condition is difficult to realize in practice (at least to the authors) because the space charge neutralization not only eliminates the space-charge fields but also seriously modifies the applied static fields.

Equation (6) gives <u>all</u> of the known forces presence in high vacuum devices under the assumptions made. We seek an explanation for the strong inward forces demonstrated in the Bennett experiments. The first term of Eq. (3) cannot become an inward force unless the ratio f of ions to electrons approaches unity. This does not usually happen in a high vacuum device but can occur within a gaseous discharge. The term v^2/c^2 cannot exceed unity and is only .039 at 10 kV and .06 at 15 kV, which under high vacuum conditions is small compared to the 1-f term. The second part of Eq. (3) (resulting from Eq. (2)) produces an inward force when the dielectric rod is charged positively. Bennett and others have shown experimentally that the dielectric rod remains negative, near cathode potential.

If the dielectric rod remains near cathode potential as reported, then electrons moving near the dielectric rod must have a low velocity corresponding to a potential near that of the dielectric rod. Therefore, the v^2/c^2 term in Eq. (6) even for the relativistic velocity experiments will be small. The only explanation of this apparent paradox known to the authors is that a gaseous discharge occurs which completely alters the voltage distributions and makes Eq. (6) not applicable.

When an energetic electron beam makes an ionization collision with a neutral molecule, the original beam electron loses only several volts of its energy and gives the created ion and free electron a volt or so of velocity in a random direction. If these ions and slow electrons are prolific, that is, if f is near unity, the ions move into regions of space-charge potential depression causing neutralization of the space charge, and more significant, serious modifications of the applied static fields. The forces are such that the charges move to readjust themselves to cancel any deviation from space-charge neutrality. The effective range over which the charges can readjust to maintain space charge neutrality is called the Debye length λ_d:

$$\lambda_d = \left[\frac{\varepsilon_o kT_e}{N_e e^2}\right]^{1/2} \qquad (7)$$

where kT_e is the energy of the electrons, N_e is the electron density, and e is the electronic charge. Any completely ionized region of linear extent greater than λ_d is called a plasma, or more generally, a plasma is an ionized region in which the net space charge is essentially zero. The plasma, or ionized region, is bounded by material walls or electrodes of the tube. At these boundaries, space-charge neutrality will not hold, and a sheath region is formed that surrounds the plasma. Any understanding of a gaseous discharge must be based not only on its plasma properties but also on the nature of the sheaths. It can be shown that both the electric field and space charge densities at the boundary edges of the sheath become very large and that the sheath thickness is approximately the Debye length λ_d.

The latest explanation of vacuum breakdown[14] is that the high currents originate from a plasma flare that rapidly spreads over the metallic cathode and also moves toward the anode. The very high breakdown current originates from this plasma flare as it moves towards the anode. A plasma sheath probably forms at the cathode which aids in providing high fields at the cathode for electron emission to the plasma flare. It seems plausible that this plasma sheath could cover not only the cathode but also the dielectric rod which is attached to the cathode and can be thought of as part of the cathode. Almost surely the plasma sheath h s high lateral conductivity because of its high space charge density. Thus, the plasma sheath surrounding the dielectric rod is the explanation offered that fits the experimental observations of the high lateral conductivity along the dielectric rod and the guidance of the current along the rod.

It has been suggested that electron bombardment induced conductivity within the dielectric rod near its surface can explain the high conductivity of the rod. It has been shown[15] that electron bombardment conductivity requires electric fields near 10^5 volts/cm and the observed bombardment induced conductivity is too low to account for the many thousands of amperes of current that have been observed to flow along the rod.

III. COLD ELECTRON EMISSION

As background information the different type of field emitters will be briefly discussed which will serve as an introduction to the field emission method used in these experiments.

1. Sharp-Point Emitters

The classical tungsten point emitters as exemplified by the work of Dyke[16] and others requires ultra-high vacuum and consist of a needle-like point cathode spaced some distance from an anode. If the current is increased beyond a few microamperes, back bombardment of the sharp point emitter by positive ions destroys the emission point.

An array of such sharp-point emitters is capable of supplying a few milliamperes of steady d-c current. Commercial sealed-off high-voltage X-ray tubes are available using this type of emitter. Recent work at Stanford Research Institute and Georgia Tech. seeks to increase the number of sharp-point emitters per unit area and thereby increase total emission current.

2. Single-Shot Emitters

A second type[17,18] of field emitter utilizes planar or hemispherical cathode surfaces of metals such as aluminum, stainless steel, or even brass. Sometimes these surfaces are sectioned with an exposed coplanar surface of insulation such as lucite, ceramic, or glass. The anode is usually a thin metallic foil spaced a few millimeters from and parallel to the cathode surface. When the pulse of high voltage (0.1 to 2 MEV) is applied to the anode, a high current flows from cathode to anode. The anode foil melts almost instantaneously, and the current flows through and beyond the anode electrode to the target. This is a single-pulse electron gun and a new anode foil must be mounted for each emission pulse. The current reaches values as high as 10^6 amperes. The emission is not sensitive to vacuum pressure, and the emission is not greatly different from a vacuum arc.

In an excellent paper Parker[14] et al give experimental evidence that the many amperes of emission originate from a plasma flare which begins at the cathode surface and moves towards the anode at a velocity of approximately 3 cm/microsecond. The plasma flare is caused by the destruction of whisker-like protrusions on the cathode surface. Field emission from the whiskers results in regneerative resistive heating, evaporation, melting, destruction, and plasma flare formation. The amount of anode current can be estimated from the space charge limited emission available from the moving plasma flare. The anode current therefore increases as the plasma flare moves towards the anode.

In the description of the cathodes no reasons are given why coplanar insulating surfaces are sometimes embedded in the cathode, but almost surely metal-insulator enhanced field emission is being utilized as described in paragraph 4 below.

3. Magnetron-Injection Gun Emitters

A third type[19-20] of field-emitter cathode is essentially the same as 2 except that an external magnetic field is employed to deflect the beam away from the anode structure. This change avoids the inconvenience of having to change anodes from pulse to pulse and allows one to obtain a current pulse about once a minute. The gun geometry is similar to the "magnetron injection gun" used in microwave tubes. A hollow beam is produced. (See Ref. 19 for details.)

4. Metal-Insulator Enhanced Field Emission

For many years it has been known,[21-22] but not generally recognized, that there is a strong tendency for insulators in vacuum to breakdown, or field emit, at the junction where the negative electrode is attached to the insulator. (Incidentally, this has been a vacuum breakdown problem of much grief in the design of vacuum devices.) A few stray electrons from almost any source, and only a few are required, strike the insulator and by secondary emission charge the insulator. There are usually more secondaries emitted by the insulator than there are primaries striking. Therefore, the insulator charges positively towards the anode potential. The insulator will charge to the potential at which the secondary emission is unity (called the "second-crossover" potential) or to the anode potential, whichever is the lesser. For this positive charging to occur it is necessary that the emitted secondary electrons "see," or be in the presence of, a collecting field for electrons such as would be the case for a nearby positive anode. The result is an unequal voltage distribution across the insulator with most of the voltage drop near the negative electrode and consequently a high field at the junction of the insulator and negative electrode. This is an alternate method of field enhancement different from the use of sharp points.

Thus, field emission and breakdown tend to occur at the junction of negative electrode and insulator where there are favorable field conditions for collection of secondaries by a nearby anode. This field emission, when it does occur, is oftentimes not self-sustaining because the insulator cannot take net current and because the voltage and/or field distribution on the insulator can change rapidly depending on the net charge received by the insulator at each point on its surface during the field emission process. If, however, the negative electrode contains trapped gases, the field emission can quickly develop into a gas discharge and vacuum breakdown.*

In Bennett's investigation[1] the insulator rod is mounted in the center of the cathode electrode. It is believed that secondary emission positive charging of the insulator rod by stray electrons causes an enhanced field at the cathode-insulator rod junction and field emission occurs at this metal-insulator junction. The field emission point quickly melts causing gas to be emitted. Positive ions are formed and move towards the cathode causing higher fields, ion bombardment, and increased electron emission. A gas discharge and plasma

*If the negative metal-insulator junction is shielded by a surrounding skirt-like metallic negative electrode such that secondaries are suppressed, then the field emission and breakdown tendencies are reduced by a factor as much as five or more. Such skirts or shields are almost essential for reliable high-voltage vacuum insulators.

quickly form which moves towards the anode as well as spreading over the cathode and the dielectric rod. In moving towards the anode, the plasma or "cathode flare" probably moves along the dielectric rod since a plasma sheath must form at the surface of the dielectric rod. The thickness of the plasma sheath is approximately the Debye length and the dielectric charges slightly negative with respect to the plasma to reject energetic electrons such that the number of electrons and ions striking the dielectric will be equal in order to maintain charge neutrality within the plasma. Charge neutrality within the plasma sheath at the surface of the dielectric will not hold, and the charge density and fields will be high -- indicative of high lateral conductivity along the plasma sheath. This proposed explanation differs from a true pinch explanation.

IV. EXPERIMENTAL RESULTS

Experiments were performed to obtain cold emission from the junction of a negative electrode and insulator rod. A copper sleeve surrounding an insulator sapphire rod, 3 mm diameter, was used as the cathode and a metallic disk-type sleeve spaced about 5 mm from the cathode was employed as the anode as shown in Fig. 2. The anode was lightly coated with fluorescent powder for the purpose of viewing the anode current. The tube (vacuum bell jar) was pumped to about 10^{-6} torr and a d-c voltage of about 9 kV applied between cathode and anode. The insulator rod charged positively by secondary emission of stray electrons to approximately the anode potential. (Only a few electrons are required to charge the rod.) The positively charged insulator produces a very high field at the cathode metal-insulator interface and causes field emission to occur at this metal-insulator junction even though the spacing between anode and cathode is relatively large. At 9 kV a field-emission current of a few microamperes flows between cathode and anode. Because the insulator rod is charged positively the current tends to be attracted towards the insulator rod and flows near or along the rod and bombards the anode very near the rod as indicated by anode fluorescence confined to a radial distance within 0.5 mm of the insulator rod. This is clearly dielectric-rod focusing, and one has a strong desire to obtain quantitative data and to increase the current. The focusing force is given in Eq. (5). However, this is a highly unstable and regenerative condition and it can only be obtained with several megohms resistance in series with the power supply for purposes of stabilization to avoid a vacuum discharge.

When the anode voltage is increased a few volts, the anode current suddenly increases and a vacuum discharge occurs. The entire anode then fluoresces and a glow or arc discharge is observed with little or no focusing due to the insulator rod. If this experiment is repeated with pulse voltages of about 2 μs duration instead of a d-c voltage, then essentially the same results are obtained except that it is exceedingly difficult to observe or measure the prebreakdown field emission current because it is only a few microamperes of pulse current and at low duty cycle. (At any moment the few microamperes will suddenly become amperes and overload the sensitive amplifiers required to detect the microamperes.) The voltage required for the prebreakdown field emission and vacuum discharge increases after several discharges from 9 kV to 10, 12, and 15 and perhaps back to 10 kV in an inconsistent fashion. It would require much more voltage (20 to 30 kV) to trigger a breakdown consistently. Therefore, a trigger mechanism had to be devised to obtain consistent current from pulse to pulse since the intended application required a beam voltage less than 15 kV.

A trigger was designed somewhat similar to that used by Lafferty[23] in triggered vacuum gap devices. A titanium film was sputtered onto the end of a ceramic cylinder as shown in Fig. 3. The film was hydrogen fired such that a large amount of hydrogen was absorbed. The outside cylinder was metalized to provide a connection to the film. A metal insert inside the cylinder provided the other connection. The film was scratched or cut with a sharp tool around the circumference such as to provide a small vacuum gap when voltage is applied to the film. A pulse of 8 kV in series with a 10K resistor will consistently cause a discharge across the gap. Electrons can be either extracted from the discharge or the discharge itself can be used to trigger a larger discharge. Because of the hydrogen firing of the titanium film the discharge is rich in hydrogen ions, but because of the presence of the titanium film and other titanium electrodes, the hydrogen can be quickly absorbed. (Titanium is the best known "getter" or absorber of hydrogen). With about 850 ma of discharge current through the film, the current that can be extracted as beam current is about 800 ma. Therefore, a large percentage of the trigger current is useful as beam current. Voltage drop across the film during the discharge is about 100 volts.

After a number of preliminary experiments, the tube shown in Fig. 4 was constructed. Cylindrical electrodes G_1 and G_2 were made of fine mesh screen and were therefore transparent to light, but substantially opaque to electric fields. Electrodes G_1 and K were made of the proper dimensions such that a cathode image could be focused onto the phosphor-coated collector C. The titanium-film cold-cathode electron gun described above was used as the electron source. Before installing the cylindrical titanium shield "S" a discharge was triggered by the electron source between G_1 and G_2 when the d-c voltage between these electrodes exceeded 4 kV. This type of arcing had been experienced on practically all previous designs. The probable explanation is that when the arc occurs across the hydrogenated titanium film, a burst of H_2 neutral molecules, ions, and electrons emerge from the film and trigger either a glow discharge or arc across any nearby accelerating electrodes with d-c voltage between them. Therefore, a shield of titanium metal was used as shown in Fig. 4. The shield either acts as a getter or shadows the titanium film electrode gap -- it is not known which of these factors is the most important. In any event, the shield is very effective and under the same conditions a d-c voltage of 18 kV (instead of the 4 kV previously) could be maintained without a discharge between G_1 and G_2 or between G_1 and K. The shield makes possible the use of accelerating and focusing electrodes. Of course, the shield itself acts as a "cathode lens" to converge electrons emerging from the cathode area. However, the electrons emerging from the titanium-film cathode are quite divergent as the following experiment shows.

The insulator rod, shown in Fig. 4, was removed for these tests. With the electrodes "K" and "G_1" at ground potential and with electrode G_2 and collector C at 10 kV, the electrons emerging from the titanium film diverge such that the beam diameter at collector C is about 7.5 cm D. as seen by the fluorescence on collector C. At 18 kV the beam is about 5 cm diameter. By operating G_1 2 kV negative, the electrons emerging from the titanium film can be made to converge to a minimum diameter at the collector "C". This minimum diameter was about 2 cm. Thus, it takes strong converging forces to cause this minimum diameter, and the minimum diameter is quite large.

The sapphire insulator rod, 3 mm in diameter, as shown in Fig. 4, was then placed into the "cathode" and collector electrodes. A sapphire rod was used because of its availability, its high secondary emission ratio and its straightness. Glass rods seem to work as well. With electrodes K and G_1 at ground potential and G_2 and collector C at + 10 kV, the beam diameter at the collector was less than 2 cm (instead of 7.5 cm), and the beam density was greatest nearest the rod as judged by the brightness of the fluorescent coating on collector C. This is a clear indication that the beam is being "converged" onto the rod -- that is, the insulating rod is providing a focusing effect. Measured currents to the collector were about 800 ma.

To obtain more quantitative information, an aperture 1.27 cm in diameter was placed in the G_2 electrode as shown in Fig. 4. The purpose was to learn how much current would pass through and reach the collector. With + 5 kV on both the collector and G_2 electrode, about 70% of the current reached the collector and at 7.5 kV more than 80% reached the collector.

An attempt was made to measure velocity distribution of the electrons within the beam by depressing the potential of collector C (Fig. 4) and monitoring the current to collector C. This was unsuccessful because the secondary emission ratio of collector C is near unity and almost as many electrons leave as arrive on collector C when it is depressed. Therefore the current to collector C is the primary current minus the secondary current, and it is difficult to determine the magnitude of the secondary current because it is not accurately known which electrodes collect the secondaries.

To determine velocity distribution of the electron flow along the rod, a Faraday-Cage retarding field collector was constructed and added to the tube as shown in Fig. 5. About 10% of the beam electrons enter the cylindrical cage through a 1.3 mm diameter aperture, "A" in Fig. 5, located at the surface of the insulator rod. Few secondaries can escape from the cylindrical cage because there is no collecting field. Therefore, when the potential of the cage is depressed, it should measure the true current entering the cage.

With the insulator in place and with 5 kV on the collector C and zero potential on electrodes G_1 and G_2 the ideal velocity distribution at the collector would be that substantially all of the electrons would reach the collector and Faraday cage at or near 5 kV velocity. Measurements indicate that with the insulator rod in place 80% of the electrons reach the collector at less than 1.5 kV energy. Without the insulator rod 80% of the electrons reach the collector at less than 3 kV energy. The experiment was repeated with 5 kV on G_2 instead of zero potential. With the insulator rod in place 60% of the electrons reach the collector at a velocity below 1 kV energy, but the remaining have a velocity nearly equal to the full 5 kV energy. Without the insulator rod the distribution was approximately the same as with the rod. It is difficult to believe this wide distribution in velocities, and the results are suspect. Indications are that the wide distribution is from either the electron source or errors in the Faraday Cage. Multiple secondary emission collisions along the insulator rod could cause a wide distribution in velocity but this is ruled out because the wide distribution is present with and without the rod. No obvious errors could be found, and therefore a thermionic emitter was designed. Thermionic emitters have a velocity distribution of less than one volt. Any errors in the Faraday Cage can therefore be observed. Disadvantages of the thermionic emitter are that the available emission current is small and the cathode easily poisons in a oil-pumped bell jar system and requires reactivation upon exposure to air.

The thermionic emitter design was tried in an attempt to obtain better values of velocity distribution. The insulator rod charged positively very near the cathode and as a result, currents were high and uncontrollable. An attempt was made to repeat the experiment with the insulator withdrawn from the cathode. However, the cathode had deactivated. The experiment was then repeated with a new oxide cathode coating. The total cathode current was 20 ma instead of the 800 ma previously. Less than 5% of this reached the Faraday Cage and as a result meaningful pulse currents to the Faraday Cage could not be read. The experiment should be repeated using d-c measurements but collector cooling may be necessary due to power dissipation.

V. CONCLUSIONS

It was shown that an insulator in contact with a cathode surface charges positively and enhances the electric field at the metal-insulator junction. This is a useful and practical way of obtaining enhanced field emission, and it is more rugged than the conventional method of achieving field emission by the use of sharp points.

It has been shown that titanium-film electrodes containing absorbed hydrogen are a useful trigger for initiating a vacuum discharge. This type of trigger can save the expense and weight of a large high-voltage modulator in a microwave system. The high-voltage electrodes can be operated at a d-c voltage, and the discharge can be initiated by a 5 to 8 kV pulse across the titanium electrodes. This is similar to a grid control.

No magnetic pinch focusing was observed at accelerating voltages as high as 18 kV. Some limited experiments were performed up to 26 kV, but no magnetic pinch focusing was observed at any time during the experiments. Power supplies were not available to go higher than 26 kV. and besides, the objective range of interest was 8 to 15 kV beam energy to match the phase velocity of the wide-band circuits of conventional traveling-wave tubes.

When an insulator rod is placed between positive and negative electrodes in vacuum, the rod tends to charge positively by secondary emission provided there is a collecting field such that the secondaries can escape and be collected. Electrons originating at or near the negative electrode will be attracted towards the insulator rod. This constitutes a focusing action caused by the secondary emission positive charging of the insulator rod and was observed and demonstrated. However, if an attempt is made to use this type of focusing in a long enclosed cylindrical structure whose radius is small compared to the axial length, then secondaries cannot escape, and the insulator rod will not maintain its positive charge. The required radial field for focusing is opposite to and in conflict with the required radial field for collection of secondaries. Therefore, this type of focusing cannot be used in a long, enclosed structure where the secondaries cannot escape in the axial direction. Thus, such focusing is not practical for present-day traveling-wave tubes.

In Bennett's experiments the insulator rod is mounted on the center of the cathode electrode. It is believed that secondary-emission charging of the insulator rod by stray electrons causes an enhanced field at the cathode-insulator rod junction and field emission occurs first at this metal-insulator junction. This field emission quickly develops into a whisker explosion and a plasma flare from which high-current electron emission takes place as explained in Ref. 14. Apparently, the plasma flare moves along the dielectric rod. In any case, the insulator rod can be viewed as an extension of the cathode such that the cathode current flows along the rod at either cathode potential or, for the secondary emission explanation, at about 5 to 10 kV above cathode potential (the "second crossover" potential). The current apparently does not flow along the rod at the full anode potential of one or more MEV. These explanations almost rule out the use of an insulator rod as a focusing device within the microwave traveling wave circuit. However, an insulator rod possibly may be useful for forming the beam and guiding it to the entrance of the microwave circuit.

VI. RECOMMENDATIONS

Experiments are needed at higher voltages (50 to 900 kV) to determine if these cold-emission high-current cathodes are useful for sealed-off high-power high-voltage microwave tubes. Some of the questions that require answers are:

(a) Can the current be controlled to a known value? Present theories of planar diodes explain the emission as originating from a plasma flare that moves from cathode to anode at approximately 3 cm/microsecond. This means that the plasma-flare space-charge-limited electron emission increases as the flare moves closer to the anode. Thus, the current is not constant with time.

(b) How does the above "moving plasma flare" explanation apply to an insulator rod cathode? Does the "flare" move along the rod at approximately the same velocity of 3 cm/microsecond?

(c) What is the distribution of emission velocities in these cathodes and on what parameters does the emission velocity depend? Does the presence of the insulator rod increase the distribution of emission velocities?

The above questions need at least a partial answer before the cathodes can be used in microwave tubes with design confidence.

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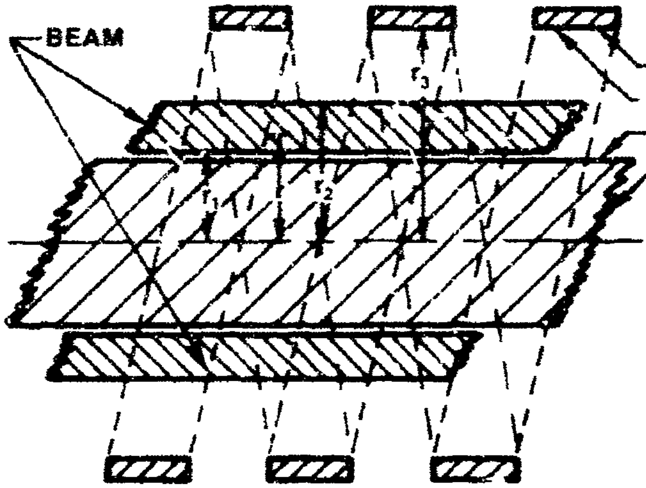

Fig. 1 — Electron beam guided by dielectric rod

Fig. 2 — Enhanced field emission from a metal-insulator junction

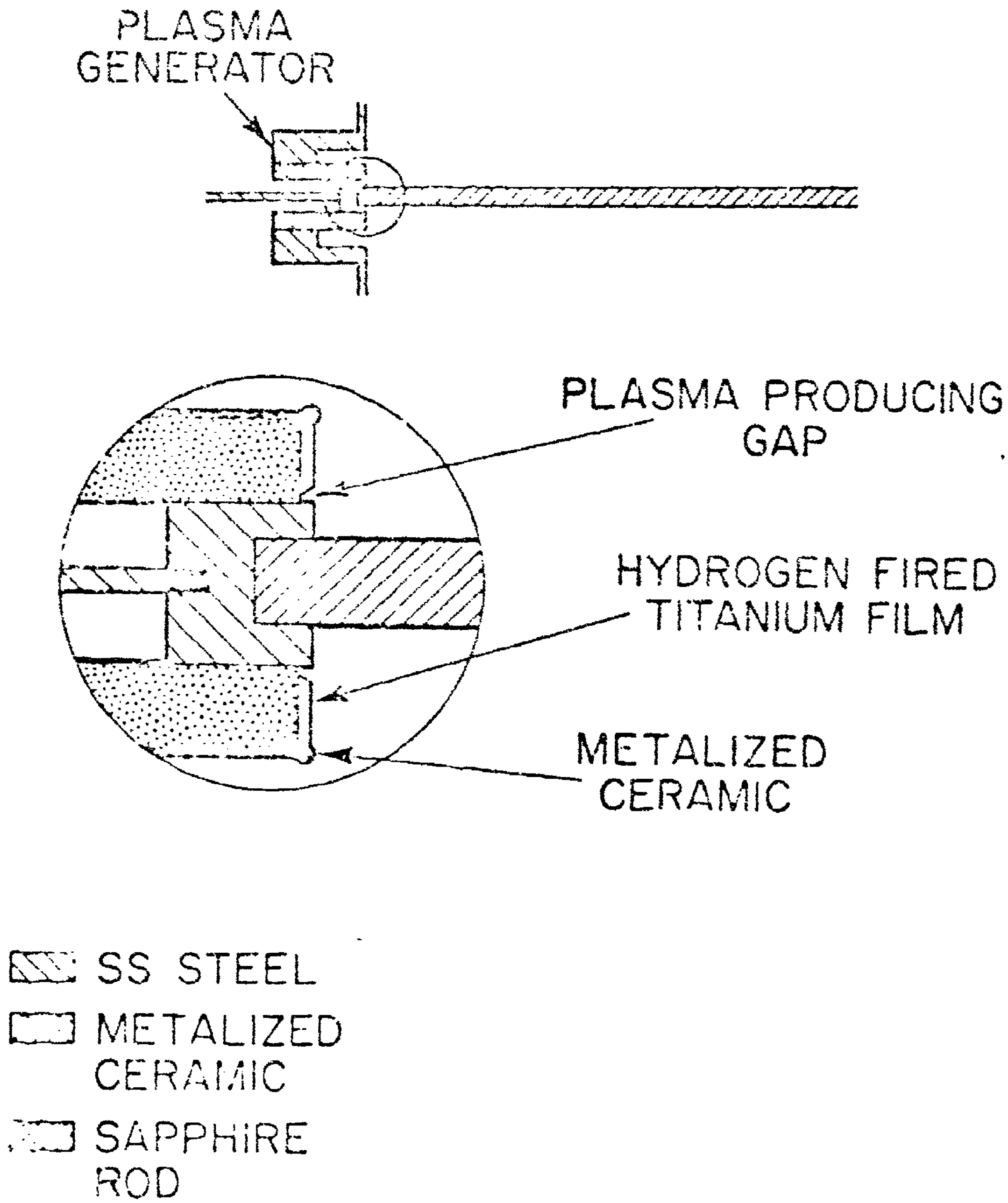

Fig. 3 - Titanium film trigger device for producing consistent electron discharges near the dielectric rod. Eliminates the need for a high voltage pulse modulator.

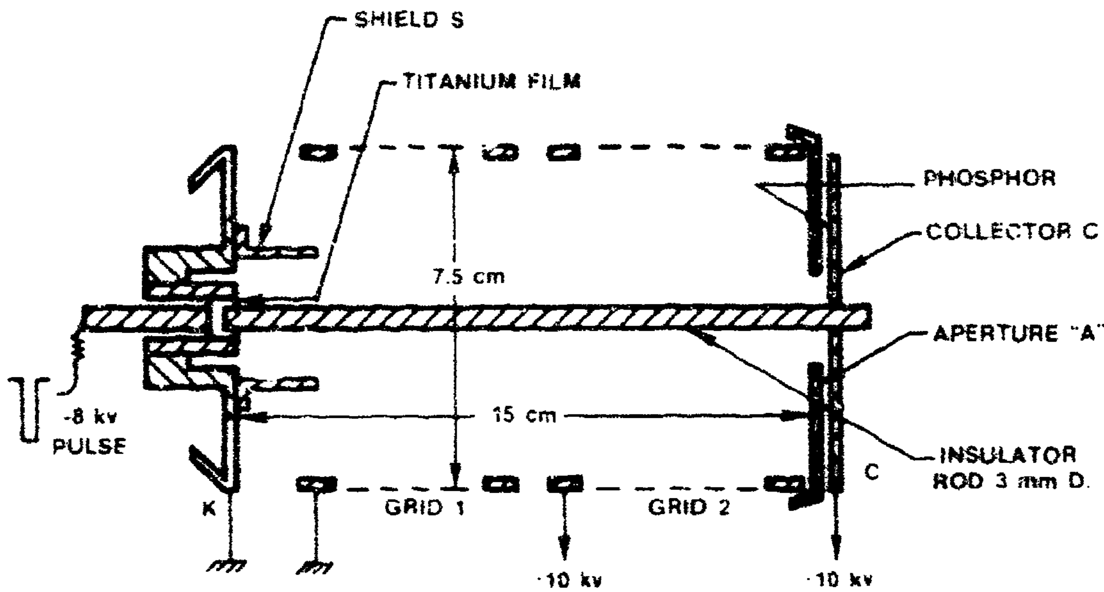

Fig. 4 — Experimental tube for observing insulator-rod focusing. Cylindrical mesh grids 1 and 2 are transparent to light in order that the beam size at Collector C can be observed by means of the phosphor deposited on Collector C. Aperture "A" added in later tests.

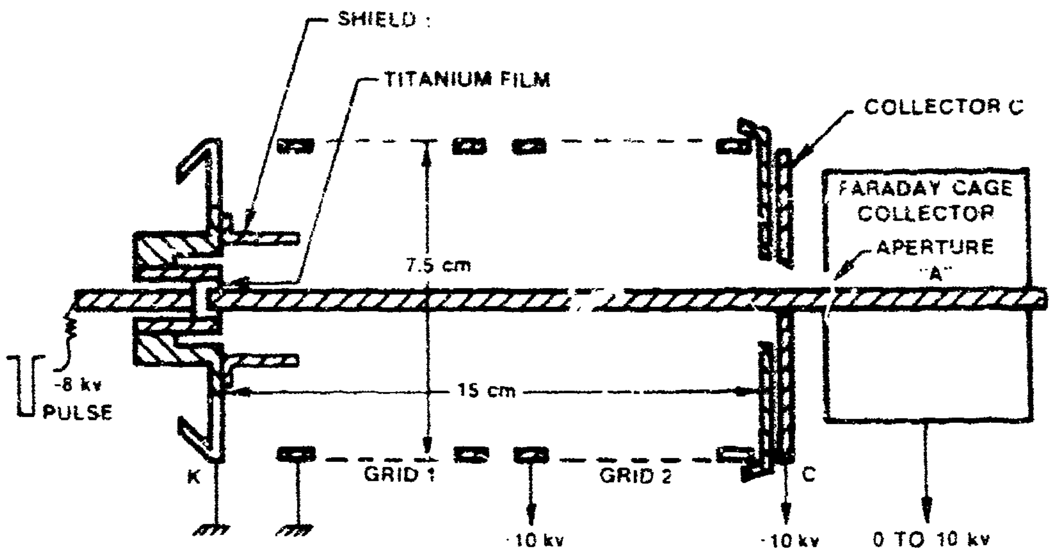

Fig. 5 — Experimental tube for measuring velocity distribution of the beam. Faraday cage collector is designed to trap a sample of the electron beam without allowing secondary electrons to escape.